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Potential for Discriminating Crop Residues from Soil by Reflectance and Fluorescence

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ABSTRACT

Crop residues left in the field after harvest can be important in controlling soil erosion. Current methods for quantifying percent crop residue cover are tedious and somewhat subjective. There is a need for new methods to quantify residue cover that are rapid, accurate, and objective. We evaluated reflectance and fluorescence techniques for discriminating crop residues from a wide range of soils. Reflectance and fluorescence spectra of 37 agricultural soils (wet and dry) and of recently harvested and weathered corn (*Zea mays* L.), soybean [*Glycine max* (L.) Merr.], sorghum [*Sorghum bicolor* (L.) Moench], and wheat (*Triticum aestivum* L.) residues were measured in the lab. Reflectance factors in the visible or near-infrared wavelengths did not uniquely distinguish all soils from all crop residues. Crop residues may be brighter or darker than a given soil, depending on soil moisture and residue age. When illuminated with ultraviolet radiation, however, the crop residues fluoresced more than most of the soils. Fluorescence of crop residues was a broad-band phenomenon centered between 420 to 520 nm and induced by a relatively broad range of excitation wavelengths centered between 350 to 400 nm. More than 90% of the crop residues <2 yr old could be discriminated from 33 of 37 dry soils and 36 of 37 wet soils using fluorescence. The threshold for discrimination can be optimized for classification accuracy for each soil. Fluorescence techniques are less ambiguous than reflectance methods and are better suited for discriminating crop residues on soils. Furthermore, if properly implemented, fluorescence techniques can be used to quantify crop residue cover in the field.

SOIL EROSION FROM CROPLAND is significantly reduced as the fraction of the soil surface covered by crop residue is increased. The management of crop residues is, therefore, an important conservation practice for reducing soil erosion and for improving water quality. By reducing the movement of eroded soil into streams and rivers, the movement of nutrients and pesticides attached to colloidal soil particles is also reduced. The overall result is less soil erosion and correspondingly improved water quality.

Rapid, accurate, and objective techniques are needed for the quantification of crop residue cover in order to evaluate the effectiveness of conservation tillage practices and to assure compliance with the Food Security Act of 1985 (Public Law 99-198) and the Food, Agriculture, Conservation, and Trade Act of 1990 (Public Law 101-624). Unfortunately, current methods for quantifying crop residue cover are difficult, tedious, and somewhat subjective.

Bonham (1989) summarized the published methods of measuring terrestrial vegetation cover into nine basic categories. Of these, only the photographic and intercept techniques are appropriate for measuring crop residue cover (Laflen et al., 1981). Morrison et al. (1993) and Corak et al. (1993) recently reviewed crop residue cover measurement techniques that are widely used or are still under development.

Intercept techniques may be grouped into line-transect and point-intercept methods. Line-transect methods measure the distance along a line covered by residue. In comparison, the point-intercept methods use a system of crosshairs, grid points, or dot matrices to define points where the presence or absence of residue is determined. Line-transect and point-intercept are the most popular methods used to estimate cover, and many modifications and refinements have been reported (Bonham, 1989). Point-intercept and line-transect methods are sometimes combined. A line is placed and the intercept is read at selected points. Accuracy of this line–point transect method depends on the length of the line and the number of points used per line. Commercially available lines are typically 15 to 30 m (50 to 100 feet) long and have 100 to 200 beads evenly spaced along the line. The line–point transect method is currently used by the USDA-SCS as the standard technique for quantifying residue cover.

A number of significant modifications to the line–point transect method are being investigated. For example, Morrison et al. (1993) described a *residue wheel* with spikes that point close to spots on the surface for observation, thus eliminating the need to stretch a line. While the wheel eliminates setting a line, it must be used carefully to minimize possible bias resulting from the observer inadvertently aiming the wheel.

Automated residue sensing schemes have attempted to replace the human judgment inherent in the line-transect method with a sensor designed to identify residue based on its reflectance characteristics. Unfortunately, unlike green vegetation, the reflectances of soils and crop residues lack a unique spectral signature (Bauer, 1975) and their reflectances typically increase monotonically with wavelength from the visible to the near-infrared (Aase and Tanaka, 1991; Baumgardner et al., 1985; Dulaney et al., 1992). A variety of soil parameters and conditions including organic matter, moisture, texture, iron oxide content, and surface roughness affect the spectral reflectance of soils (Condit, 1970; Stoner et al., 1980). Crop residues and soils are often spectrally similar, differing only in amplitude at a given wavelength. In fact, the reflectance of residue at a particular wavelength may be higher or lower than the reflectance of the soil (Aase and Tanaka, 1991; McMurtrey et al., 1993; Stoner et al., 1980). This makes discrimination of crop residues and soils difficult or nearly impossible using conventional reflectance techniques alone.

The *photographic method* consists of taking single vertical photographs or vertical stereographic pairs of photographs of the surface and visually estimating the fraction

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Abbreviations: EEM, excitation–emission matrix; FOV, field of view; NADPH, nicotinamide adenine dinucleotide phosphate, reduced; RFI, relative fluorescence intensity; WEPP, Water Erosion Prediction Project.

of the soil covered by residue. An important advancement of the photographic technique is computer-aided analysis of black-and-white, color, or multispectral video images. Once a video image is captured, a computer can be used to quickly analyze and classify the image into soil and residue classes using objective procedures. Classification errors occur when the spectral differences between soil and residue classes are not sufficiently large for discrimination.

Field procedures for photography and video imaging require approximately the same amount of time; however, video images may be immediately evaluated, without the delay of film processing. Based on research experience, Morrison et al. (1993) estimated that video image analysis procedures would require ≤ 2 min per image, as compared with 20 min per slide for the minimum of three 200-dot screens. Once again, problems arise when the contrast between soil and residue is small.

All of the previous automated methods have relied on measuring reflected radiation. McMurtrey et al. (1993) demonstrated in the lab that crop residues fluoresce more than soils in a broad band centered at 440 nm when illuminated with ultraviolet radiation at 337 nm. Chappelle et al. (1991) hypothesized that the fluorescence in the blue region of the spectrum from plants may be due to fluorescence of lignin, riboflavin, and NADPH. These compounds are abundant in plants but scarce in soils.

Our overall objective was to develop new methods to quantify crop residue cover that are rapid, accurate, and objective. In this paper, we discuss the potential for discriminating crop residues from a wide range of soils using reflectance and fluorescence techniques.

MATERIALS AND METHODS

Soils

Samples of 37 major U.S. cropland and rangeland soils, representing 8 soil orders and 14 suborders, were included in this study (Table 1). Many of the soils were acquired as part of the Water Erosion Prediction Project (WEPP) and have extensive characterization data available (Lane and Nearing, 1989; Soil Survey Staff, 1990). Additional soils were acquired near Beltsville, MD, Bushland, TX, Hansen Butte, ID, and Kimberly, ID. Each soil was air-dried, crushed, and passed through a 2-mm screen.

Crop Residues

Residues of recently harvested and weathered corn (*Zea mays* L.), soybean [*Glycine max* (L.) Merr.], sorghum [*Sorghum bicolor* (L.) Moench], and wheat (*Triticum aestivum* L.) were acquired from agricultural fields near Beltsville, MD, and Bushland, TX. The samples of residue were air-dried in a glasshouse and were cut as needed to fill 20-cm-diam. dishes. A portion of each sample was ground to pass a 1-mm screen. Although no attempt was made to separate the residue samples before grinding, some samples were separated into leaves, stems, or other parts for the reflectance and fluorescence measurements. The ages of the residues ranged from <1 wk after harvest to >2 yr after harvest for dryland wheat and sorghum.

Reflectance Factors

Reflectance spectra of each soil and residue were measured at 5-nm increments over the 400- to 1000-nm wavelength range

Table 1. Soil taxonomic classification of cropland and rangeland soils.†

Soil series	Location	Classification
		Alfisols
Academy	Fresno, CA	fine-loamy, mixed, thermic Mollic Haploxeralf
Amarillo	Big Springs, TX	fine-loamy, mixed thermic Aridic Paleustalf
Frederick	Hancock, MD	fine, mixed, mesic Typic Hapludalf
Lewisburg	Columbia City, IN	fine, illitic, mesic Typic Hapludalf
Mexico	Columbia, MO	fine, montmorillonitic, mesic Udollic Ochraqualf
Miami	Waveland, IN	fine-loamy, mixed, mesic Typic Hapludalf
Miamian	Dayton, OH	fine, mixed, mesic Typic Hapludalf
Opequon	Flintstone, MD	fine, mixed, mesic Typic Hapludalf
		Aridisols
Portneuf‡	Twin Falls, ID	coarse-silty, mixed, mesic Durixerollic Calciorthid
		Inceptisols
Codorus	Beltsville, MD	fine-loamy, mixed, mesic Fluvaquentic Dystrochrept
Grenada	Como, MS	fine-silty, mixed, thermic Typic Fragiochrept
Hersh	Ord, NE	coarse-loamy, mixed, mesic Typic Ustochrept
Manor	Ellicott City, MD	coarse-loamy, micaceous, mesic Typic Dystrochrept
Woodward	Buffalo, OK	coarse-silty, mixed, thermic Typic Ustochrept
		Mollisols
Barnes	Morris, MN	coarse-loamy, mixed Udic Haploboroll
Clarion	Ames, IA	fine-loamy, mixed, mesic Typic Hapludoll
Keith‡	Albin, WY	fine-silty, mixed, mesic Aridic Argiustoll
Los Banos	Los Banos, CA	fine-loamy, mixed, thermic Typic Haploxeroll
Monona	Castana, IA	fine-silty, mixed, mesic Typic Hapludoll
Palouse	Pullman, WA	fine-silty, mixed, mesic, pachic Ultic Haploxeroll
Pullman	Bushland, TX	fine, mixed, thermic Torrertic Paleustoll
Sharpsburg	Lincoln, NE	fine, montmorillonitic, mesic Typic Argiudoll
Sverdrup	Morris, MN	sandy, mixed Udic Haploboroll
Walla Walla	Pullman, WA	coarse-silty, mixed, mesic Typic Haploxeroll
Williams	McClusky, ND	fine-loamy, mixed Typic Argiboroll
Zahl	Bainville, MT	fine-loamy, mixed Entic Haploboroll
		Oxisols
Gaston	Salisbury, NC	fine, kaolinitic, thermic Inceptic Eutrudox
		Spodosols
Caribou	Presque Isle, ME	coarse-loamy, mixed, frigid Typic Haplorthod
		Ultisols
Bonifay	Tifton, GA	loamy, siliceous, thermic grossarenic Plinthic Paleudult
Collamer	Ithaca, NY	fine-silty, mixed, mesic Glossoboric Hapludult
Hiwassee	Watkinsville, GA	clayey, kaolinitic, thermic Rhodic Kanhapludult
Tifton	Tifton, GA	fine-loamy, siliceous, thermic Plinthic Kandiudult
		Vertisols
Pierre	Wall, SD	very-fine, montmorillonitic, mesic Typic Torrert

† Classification according to Soil Survey Staff (1990).
‡ Additional samples: Portneuf-2 and Portneuf-3 from Kimberly, ID; Portneuf-4 from Hansen Butte, ID; Keith-2 from Scottsbluff, NE.

with a spectroradiometer and telescope (Model LI-1800,[1] Li-Cor, Lincoln, NE) positioned at nadir. Each sample was illuminated at 20° from nadir with nearly collimated radiation from a xenon lamp with appropriate transfer optics (Kestner et al., 1988). Reflectance factors were calculated as the ratio of sample radiance divided by the radiance of a Spectralon (Labsphere, North Sutton, NH) reference surface and corrected for the reflectance of the reference surface (Biehl and Robinson, 1983). Soil samples were measured dry and wet (field capacity). The wet samples were prepared by saturating the soil with water and allowing it to drain and equilibrate in an insulated box over free water for at least 1 wk. Although the reflectance factors of both whole and ground residue samples were measured, only data from the whole samples are reported.

Excitation–Emission Matrices

A spectrofluorometer (Model 8000C, SLM Instruments, Urbana, IL) was used to determine the excitation–emission matrices (EEMs) of representative samples of the residues and soils. The excitation monochrometer was stepped at 10-nm intervals over the 250- to 800-nm wavelength range. The emission monochrometer was stepped at 5-nm intervals over the 300- to 850-nm wavelength range. The spectrofluorometer was operated in the photon counting mode with an integration time of 0.2 s per emission interval. Long-pass Schott glass filters were inserted in the emission light path to remove higher order effects. The data were corrected for filter transmittance and resampled into a 20- by 20-nm data matrix for three-dimensional plotting (Satterwhite, 1990).

Relative Fluorescence Intensities

The soil and residue samples were illuminated with longwave ultraviolet lamps (Model ML-49, Ultra-Violet Products, San Gabriel, CA) filtered with Schott UG-1 glass. The peak emission wavelength of the lamps was at 365 nm. The emitted visible radiation was measured with a photomultiplier tube (Model 928, Hamamatsu, Bridgewater, NJ) fitted with a 435-nm longpass filter. The diameter of the field of view (FOV) of the detector was 1 cm. The soil and residue samples were placed in 20-cm-diam. dishes and rotated slowly in the FOV as the output voltage from the photomultiplier tube was recorded on a data logger. At least 20 observations per sample were acquired, to assess the variability of the fluorescence signal. After the sieved soils were measured dry, they were sprayed with water until no more changes in color were observed and remeasured (moist). The soils were then saturated with water and allowed to dry in a glasshouse for several days and form a crust. The crusted soils were also measured dry and moist. The whole residues (i.e., as collected from the field) were measured dry and moist; ground residues were measured only dry. Several of the ground samples of the crop residues were used as fluorescence reference targets and were measured repeatedly at the beginning and the end of each day. The day-to-day changes in the fluorescence of the reference samples were small. The dark current of the system was measured by closing a shutter on the detector assembly and recording the output voltage, which was usually negligible. Relative fluorescence intensity (RFI) was calculated as the photomultiplier tube output voltage corrected for the dark current and normalized for day-to-day changes in the fluorescence of the reference samples.

[1] Company and trade names are given for the benefit of the reader and do not imply any endorsement of the product or company.

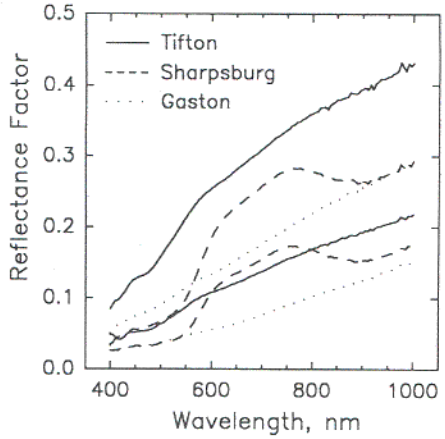

Fig. 1. Three pairs of reflectance spectra for selected soils. For each pair, the upper spectra is for dry soil and the lower spectra is for wet soil.

RESULTS AND DISCUSSION

Reflectance Factors

Three pairs of reflectance spectra for representative soils are shown in Fig. 1. The upper spectrum of each pair is for air-dry soil and the lower spectrum is for wet (field capacity) soil. For example, the reflectance factor at 650 nm of Tifton soil may range from 0.12 when wet to 0.28 when dry. Reflectance factors in four wavelength bands for the wet and dry soils are given in Table 2. In each band, the reflectance factor nearly doubled as the soil dried from field capacity to air-dry. Although surface roughness affects reflectance of individual soils, the reflectance factors in Table 2 represent the wide range of values expected in the field.

Figure 2 illustrates the wide range in reflectance factors observed in whole corn residue sampled from a single field at 8 mo after harvest. For example, the reflectance factor of the corn residue varied from 0.09 to 0.52 at 650 nm. Much of the variation in reflectance factors appears to be associated with the extent of the growth of microbial colonies on the surface of the residue. Portions of the corn residue were light brown where microbial growth was minimal, while other portions were nearly black where microbial growth was greatest. Table 3 gives the mean and standard deviation of reflectance factors of the crop residues.

Note the considerable overlap in the magnitude of reflectance factors for the residues and any of the three soils (Fig. 1 and 2). Crop residues may be brighter or darker than a given soil, depending on soil moisture, residue age, and the extent of microbial degradation of the residue (Tables 2 and 3). Thus, for the reflectance data, no single wavelength in the 400- to 1000-nm wavelength range appears capable of uniquely distinguishing all soils from all crop residues. These results agree with conclusions of Aase and Tanaka (1991) and Gausman et al. (1975), but for a much broader range of soils than included in their reports. Nonetheless, discrimination of residues and soils may be possible using a combination of visible and near-infrared reflectance factors plus the wavelength of the maximum first derivative (Dulaney et al., 1992).

Table 2. Reflectance factors of wet and dry soils in four wavelength bands. Each entry is the mean of three observations per sample.

	TM1‡		TM2		TM3		TM4	
Soil series†	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
Alfisols								
Academy	0.10	0.07	0.14	0.08	0.17	0.09	0.24	0.13
Amarillo	0.07	0.04	0.13	0.07	0.23	0.13	0.32	0.18
Frederick	0.13	0.05	0.20	0.07	0.29	0.11	0.38	0.15
Lewisburg	0.16	0.06	0.24	0.10	0.31	0.13	0.38	0.18
Mexico	0.11	0.05	0.14	0.06	0.19	0.08	0.30	0.13
Miami	0.14	0.05	0.23	0.08	0.31	0.13	0.39	0.18
Miamian	0.12	0.05	0.19	0.09	0.25	0.12	0.31	0.16
Opequon	0.16	0.07	0.27	0.12	0.37	0.18	0.43	0.23
Aridisols								
Portneuf-1	0.23	0.14	0.30	0.18	0.37	0.21	0.43	0.24
Inceptisols								
Grenada	0.13	0.05	0.23	0.11	0.34	0.17	0.43	0.24
Hersh	0.14	0.06	0.19	0.09	0.25	0.12	0.35	0.18
Manor	0.12	0.07	0.22	0.11	0.32	0.17	0.39	0.21
Woodward	0.06	0.04	0.10	0.06	0.18	0.10	0.27	0.15
Mollisols								
Barnes	0.07	0.03	0.09	0.04	0.13	0.06	0.21	0.09
Clarion	0.10	0.05	0.15	0.07	0.20	0.10	0.28	0.15
Keith-1	0.09	0.05	0.12	0.07	0.16	0.08	0.22	0.12
Keith-2	0.10	0.04	0.13	0.05	0.17	0.07	0.24	0.11
Los Banos	0.08	0.04	0.12	0.06	0.16	0.09	0.20	0.12
Monona	0.10	0.04	0.15	0.06	0.21	0.09	0.30	0.15
Palouse	0.08	0.05	0.12	0.06	0.17	0.08	0.24	0.12
Sharpsburg	0.09	0.04	0.12	0.05	0.16	0.07	0.23	0.11
Sverdrup	0.06	0.05	0.08	0.06	0.12	0.07	0.20	0.12
Walla Walla	0.08	0.05	0.12	0.06	0.16	0.07	0.23	0.10
Williams	0.08	0.05	0.11	0.06	0.15	0.08	0.22	0.11
Zahl	0.08	0.04	0.11	0.06	0.15	0.08	0.20	0.11
Oxisols								
Gaston	0.06	0.03	0.12	0.07	0.23	0.14	0.27	0.16
Spodosols								
Caribou	0.17	0.06	0.25	0.09	0.32	0.13	0.38	0.17
Ultisols								
Bonifay	0.19	0.06	0.26	0.09	0.33	0.12	0.41	0.18
Collamer	0.18	0.08	0.27	0.11	0.33	0.15	0.39	0.19
Hiwassee	0.13	0.06	0.21	0.09	0.32	0.16	0.39	0.20
Tifton	0.15	0.06	0.22	0.09	0.29	0.12	0.37	0.18
Vertisols								
Pierre	0.08	0.05	0.11	0.07	0.14	0.08	0.18	0.11

† Classification according to Soil Survey Staff (1990).
‡ TM1, 450–520 nm; TM2, 520–600 nm; TM3, 630–690 nm; TM4, 760–900 nm.

Excitation–Emission Matrices

Earlier work (McMurtrey et al., 1993) clearly showed that crop residues fluoresce when excited by an ultraviolet laser at 337 nm; however, little is known about the characteristics of the fluorescence spectra for other excitation wavelengths. Therefore, we used a spectrofluorometer to examine both the excitation and emission spectra of selected residues and soils. The EEM of a representative sample of corn residue is presented in Fig. 3. The contour plot of the EEM (Fig. 4) showed peak fluorescence at 480 nm for an excitation at 400 nm. The light brown-colored corn shuck had broad-band emissions over the 400- to 690-nm region for excitations of 300 to 520 nm. The excitation–emission matrices of other crop residues were similar.

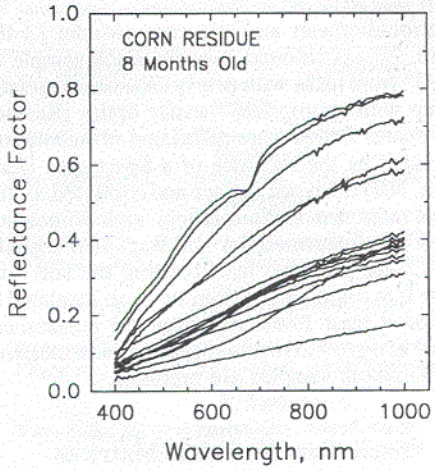

Fig. 2. Representative reflectance spectra of corn residue sampled 8 mo after harvest from a field near Beltsville, MD. Note the wide range in reflectance factors over the whole wavelength interval.

Although the fluorescence of ground crop residues was 2 to 12 times higher than that of the whole residues, the wavelengths of the excitation and emission maxima were unchanged (Table 4). The maximum fluorescence for all residues was in the 455- to 495-nm wavelength interval for excitation at 400 nm. Grinding exposed more surfaces to the excitation radiation and enhanced fluorescence. The EEM data illustrate that the fluorescence of crop residues is a broad-band phenomenon that can be induced by a relatively broad range of excitation wavelengths.

The soils had low-intensity broad-band emissions over the 400- to 690-nm region for excitations of 300 to 600 nm (Fig. 5), which is typical of many soils (Satterwhite, 1990). The fluorescence of the soils were one to two orders of magnitude less than the fluorescence of the crop residues. An exception was the Portneuf soil, which had fluorescence intensities nearly an order of magnitude higher than the other soils sampled (Table 4). The Portneuf soil is high in $CaCO_3$ (5.2% in the top 20 cm), which may have contributed to its higher fluorescence (Warren, 1969).

Table 3. Reflectance factors of dry crop residues in four wavelength bands.

			TM1‡		TM2		TM3		TM4	
Crop†	Age	No.	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Corn	1 wk	20	0.20	0.089	0.28	0.110	0.39	0.129	0.57	0.112
	2 mo	18	0.17	0.054	0.23	0.062	0.31	0.078	0.43	0.107
	8 mo	27	0.14	0.072	0.20	0.099	0.28	0.020	0.39	0.151
Soybean	1 wk	18	0.11	0.051	0.18	0.069	0.28	0.089	0.48	0.112
	1 yr	18	0.15	0.028	0.18	0.033	0.22	0.043	0.29	0.054
Wheat	1 wk	10	0.16	0.053	0.24	0.068	0.35	0.087	0.48	0.100
	3 mo	10	0.12	0.044	0.16	0.054	0.23	0.066	0.35	0.071

† Crop residues from Beltsville, MD.
‡ TM1, 450–520 nm; TM2, 520–600 nm; TM3, 630–690 nm; TM4, 760–900 nm.

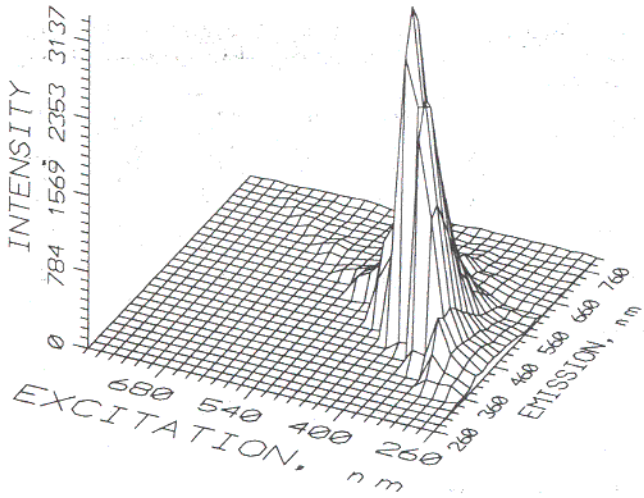

Fig. 3. Excitation–emission matrix (EEM) data for 8-mo-old corn shuck. Maximum fluorescence was observed at an excitation wavelength of 400 nm and emission wavelength of 480 nm. Fluorescence intensity units are photon s^{-1}.

Relative Fluorescence Intensities

The relative fluorescence intensities (RFI) of dry-crusted and wet-crusted soils are shown in Table 5. The RFI data for dry-loose and wet-loose soils were similar (data not shown). Although the mean RFI values for the dry soils range from 5.9 for Gaston to 47.9 for Portneuf, RFI values were <20.0 for 32 of the 37 soils examined. Moreover, three of the five soils with RFI > 20.0 were samples of Portneuf soil from different locations in Idaho (Table 1). Three of the four samples of Portneuf soil had high RFI values for both wet and dry conditions. The remaining two soils with RFI > 20.0 (i.e., Hersh and Tifton) exceeded 20.0 only when they were dry and crusted.

Moisture reduced (quenched) fluorescence in a predictable manner. A single regression equation adequately described the changes in RFI due to moisture for both crop residues and soils (Fig. 6). The intercept term was not significantly different from 0 (α = 0.05, n = 120) and was dropped from the final equation. The RFI of a wet sample was described as a simple function of the RFI of a dry sample. Thus, the relative difference in fluorescence between crop residues and soils remained fairly constant regardless of moisture conditions. The greatest RFI contrast would occur for a scenario with dry residue on wet soil.

Although the range of RFI values for the crop residues (Table 6) was much greater than the RFI observed for the soils (Table 5), there was some overlap in RFI values. The RFI values observed in the crop residues were skewed to high values. In general, older crop residues have lower minimum and lower maximum RFI values than recently

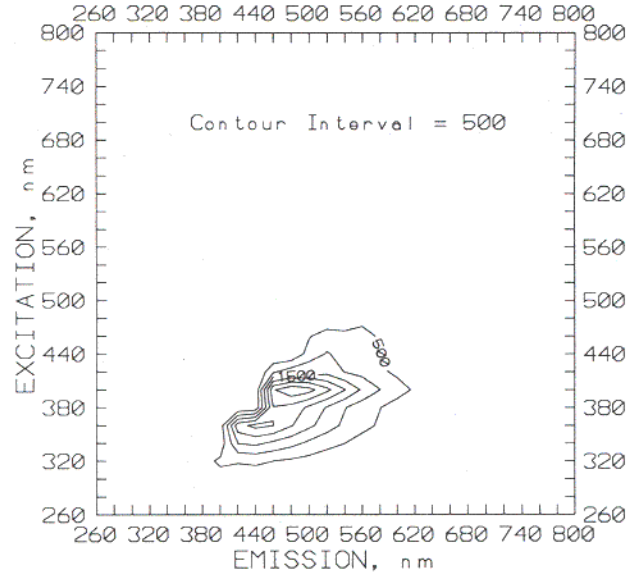

Fig. 4. Contour plot of the excitation–emission matrix (EEM) data presented in Fig. 3. The contour interval is 500 photon s^{-1}.

Table 4. Emission and excitation wavelengths of maximum fluorescence intensity for selected crop residues and soils. Data were acquired with a scanning spectrofluorometer. Note the much greater fluorescence intensity for the crop residues than for three of the four soils.

Sample	Age	Emission	Excitation	Fluorescence intensity
		nm		photon s^{-1}
Corn				
Ground	2 mo	480	400	13 631
Shuck	2 mo	490	400	8 729
Shuck	8 mo	480	400	3 396
Shuck	8 mo	485	400	658
Stalk	8 mo	495	400	506
Soybean				
Ground	1 yr	475	400	12 080
Stems	1 yr	455	400	901
Soil series†				
Gaston		680	650	154
Grenada		655	600	211
Portneuf		490	400	1 643
Sverdrup		490	400	125

† See Table 1 for taxonomic description.

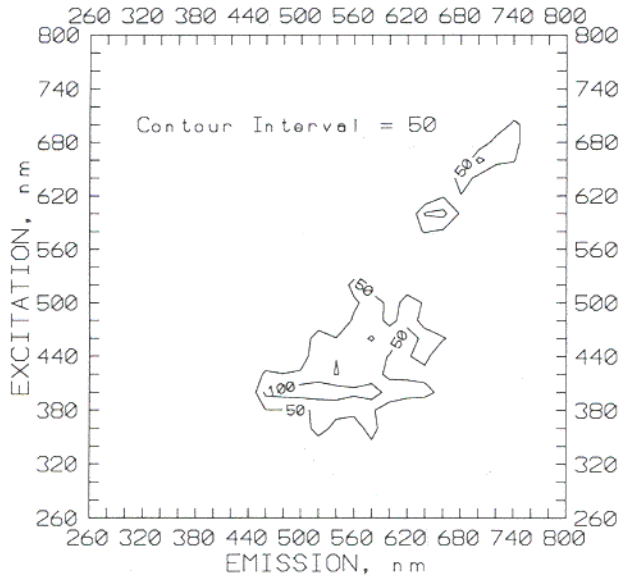

Fig. 5. Contour plot of the excitation–emission matrix (EEM) data for dry Grenada soil. The contour interval is 50 photon s^{-1}. Note the contour interval for the corn residue in Fig. 4 is 10 times greater than the interval for this soil.

Table 5. Relative fluorescence intensity (RFI) of dry-crusted and wet-crusted soils.

Soil series†	Dry crusted Mean	Dry crusted SD	Wet crusted Mean	Wet crusted SD
Alfisols				
Amarillo	12.0	0.52	5.7	0.18
Frederick	9.0	0.29	4.4	0.31
Lewisburg	9.7	0.57	5.0	0.24
Mexico	9.2	0.56	5.2	0.25
Miami	11.0	0.68	5.3	0.26
Miamian	11.2	1.83	6.0	0.46
Opequon	11.0	0.68	6.2	0.30
Aridisols				
Portneuf-1	47.9	1.28	29.3	0.62
Portneuf-2	22.9	0.98	14.2	0.48
Portneuf-3	28.5	0.84	12.8	0.46
Portneuf-4	15.0	0.38	8.7	0.27
Inceptisols				
Grenada	9.5	0.38	5.0	0.23
Hersh	21.4	0.95	8.5	0.21
Manor	13.8	0.84	6.1	0.51
Woodward	14.1	0.99	5.5	0.23
Mollisols				
Academy	10.5	0.46	5.7	0.17
Barnes	10.1	0.83	5.4	0.49
Clarion	7.4	0.35	5.2	0.29
Keith-1	11.1	0.46	6.2	0.22
Keith-2	12.8	1.16	6.0	0.36
Los Banos	9.5	0.90	5.8	0.42
Monona	8.4	0.66	5.1	0.26
Palouse	6.1	0.44	3.9	0.09
Pullman	10.2	0.93	6.3	0.24
Sharpsburg	7.3	0.50	5.1	1.08
Sverdrup	8.4	0.47	5.0	0.17
Walla Walla	7.6	0.25	5.1	0.31
Williams	8.1	0.21	5.3	0.48
Zahl	8.3	0.21	5.5	0.40
Oxisols				
Gaston	5.9	0.27	4.2	0.34
Spodosols				
Caribou	12.4	1.40	5.5	0.46
Ultisols				
Bonifay	14.2	0.57	6.7	0.32
Collamer	10.7	0.35	5.4	0.15
Hiwassee	9.5	0.30	5.9	0.18
Tifton	21.5	2.64	7.0	0.23
Vertisols				
Pierre	8.8	0.57	5.5	0.48

† Classification according to Soil Survey Staff (1990).

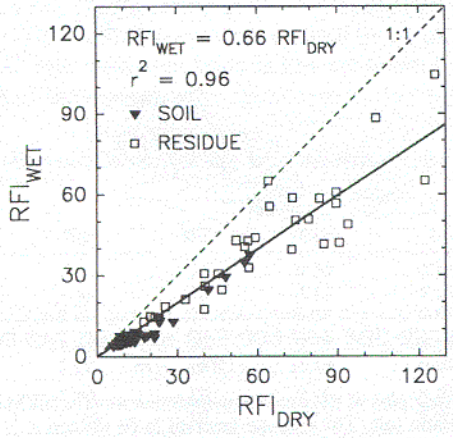

Fig. 6. Relationship of fluorescence of wet soils and crop residues to fluorescence of dry soils and crop residues. $RFI_{wet} = 0.66\ RFI_{dry}$; standard error of slope = 0.013; $n = 120$; adjusted $r^2 = 0.96$.

Table 6. Minimum, maximum, mean and standard deviation (SD) of relative fluorescence of recently harvested and weathered crop residues.

Crop	Age	No.	Min	Max	Mean	SD
Corn†	1 wk	70	42.9	239.4	97.7	43.3
	2 mo	170	23.6	124.8	58.1	23.9
	8 mo	140	13.6	167.5	52.9	30.1
Sorghum‡	1 yr	150	26.5	259.6	101.4	43.4
	3 yr	180	14.0	202.2	64.0	39.3
Soybean†	1 wk	120	15.4	149.5	76.8	32.5
	1 yr	70	17.1	77.2	48.0	17.3
Wheat†	1 wk	70	20.2	56.1	38.9	9.5
	3 mo	70	16.0	52.0	34.2	9.7
Wheat‡	2 mo	250	22.6	119.6	63.1	19.7
	1 yr	120	17.3	72.8	40.1	14.1
	2 yr	150	11.2	51.6	25.8	10.7
All residues		1560	11.2	259.6	59.6	35.1

† Crop residues from Beltsville, MD.
‡ Crop residues from J.L. Steiner at Bushland, TX.

harvested residues (Table 6). Thus, as crop residues decompose, their RFI values approach that of the soil.

Some of the variability in RFI is due to the size of the residue pieces relative to the FOV of the detector. In some cases (e.g., wheat and soybean), the 1-cm-diam. FOV of the detector was larger than the pieces of residue, and multiple pieces of randomly oriented residue were included in the FOV. In other samples (e.g., corn and sorghum), the residue pieces were >1 cm, but there were also gaps between the pieces >1 cm. In both cases, the RFI data were acquired randomly, as the sample tray was rotated with no provision for positioning the FOV. This sampling scheme provided a more realistic estimate of the variation in RFI, such as one might expect in the field.

To illustrate the separability of the soils and residues based on RFI, we chose various thresholds that span the range of RFI values for soils (Table 5). Each observation of RFI was classified as residue if it exceeded the threshold and as soil if it was less than or equal to the threshold. For an RFI threshold of 10.0, all of the residues had higher RFI values and were correctly classified (Table 7). All of the residues had minimum RFI values (Table 6) greater than the mean RFI of 16 of the 37 dry soils, in addition

Table 7. Percent correct classification of relative fluorescence intensity (RFI) of all wet and dry crop residues and soils. Each RFI observation was classified as a residue if it exceeded the threshold and as soil if it was less than or equal to the threshold.

Crop	Age	No.	RFI threshold 10	20	30	40
Corn†	1 wk	70	100	100	100	100
	2 mo	170	100	100	99	95
	8 mo	140	100	99	86	60
Sorghum‡	1 yr	150	100	100	99	95
	3 yr	180	100	96	76	63
Soybean†	1 wk	120	100	98	93	85
	1 yr	70	100	97	76	67
Wheat†	1 wk	70	100	100	77	54
	3 mo	70	100	93	59	33
Wheat‡	2 mo	250	100	100	99	91
	1 yr	120	100	96	67	45
	2 yr	150	100	59	31	12
All residues		1560	100	95	82	69

† Crop residues from Beltsville, MD.
‡ Crop residues from J.L. Steiner at Bushland, TX.

to being greater than the mean RFI of 32 of the 37 wet soils (Table 5). For an RFI threshold of 20.0, >90% of the residues were correctly classified, except for the 2-yr-old wheat residues from Bushland, TX (Table 7). This means that more than 90% of the residues <2 yr old had minimum RFI values greater than the mean RFI of 32 of the 37 dry soils and greater than the mean RFI of 36 of the 37 wet soils.

CONCLUSIONS

We conclude, therefore, that this fluorescence technique provides a method to discriminate crop residues from many agricultural soils and could be used to quantify crop residue cover, if properly implemented. Furthermore, if one knows the RFI of a particular soil, then the discrimination threshold can be set to optimize classification accuracy. Based on our laboratory study of a wide range of soils, the RFI threshold seems broadly applicable and may not require resetting for within-field changes in soil type. Our conclusions contrast sharply with previous investigations using visible and near-infrared reflectance factors to discriminate between soil and crop residues. In those studies, the differences in reflectance factors were generally small, discrimination was ambiguous, and thresholds for discrimination had to be adjusted for soil moisture and soil type (Aase and Tanaka, 1991; Gausman et al., 1975).

In summary, it appears that crop residues can be accurately discriminated from a wide range of wet and dry soils using fluorescence techniques. One caveat is that these results are from laboratory studies with pure pixels of crop residues and pure pixels of soil. In practice, there will be mixed pixels with varying proportions of soil and crop residues, which will decrease overall classification accuracy. Nevertheless, given the limited range of the RFI values observed for most soils, it seems possible to empirically set a threshold for discriminating crop residues from soils that optimizes classification accuracy. Work is currently underway to develop a fluorescence instrument capable of operating in the field.

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